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***Abstract*— In this paper, we address the problem of efficiently streaming a set of heterogeneous videos from a remote server through a proxy to multiple asynchronous clients so that they can experience playback with low startup delays. We develop a technique to analytically determine the *optimal* proxy prefix cache allocation to the videos that minimizes the aggregate network bandwidth cost. We integrate proxy caching with traditional server-based reactive transmission schemes such as batching, patching and stream merging to develop a set of proxy-assisted delivery schemes. We quantitatively explore the impact of the choice of transmission scheme, cache allocation policy, proxy cache size, and availability of unicast versus multicast capability, on the resultant transmission cost. Our evaluations show that even a relatively small prefix cache (10%-20% of the video repository) is sufficient to realize substantial savings in transmission cost. We find that carefully designed proxy-assisted reactive transmission schemes can produce significant cost savings even in predominantly unicast environments such as the Internet.**

I. Introduction

The emergence of the Internet as a pervasive communication medium, and a mature digital video technology have led to the rise of several networked streaming media applications such as live video broadcasts, distance education, corporate telecasts, etc. However, due to the high bandwidth requirements and the long-lived nature (tens of minutes to a couple of hours) of digital video, server and network bandwidths are proving to be major limiting factors in the widespread usage of video streaming over the Internet. This is further complicated by the fact that the client population is likely to be large, with different clients asynchronously issuing requests to receive their chosen media streams. Also different video clips can have very different sizes (playback bandwidths and durations) and popularities. In this paper, we address the problem of efficiently streaming a set of heterogeneous videos from a remote server through a proxy to multiple asynchronous clients so that they can experience playback with low startup delays. Before presenting the main contributions, we discuss some key challenges and limitations of existing techniques in reaching this goal.

Existing research has focused on developing *reactive* transmission schemes that use multicast or broadcast connections in innovative ways to reduce server and network loads, for serving a popular video to multiple asynchronous clients. The techniques are *reactive* in that the server transmits video data only on-demand, in response to arriving client requests. *Batching*, *patching* and *stream merging* belong to this category. In batching, the server batches requests that arrive close together in time [1], and multicasts the stream to the set of clients. In patching or stream tapping [2], [3], [4], the server streams the entire video sequentially to the very first client. A later client receives (part of) its future playback data by listening to an existing ongoing multicast of the same video, with the server transmitting afresh only the missing prefix. Stream merging [5] is a related technique where all streams (complete and prefix) are transmitted using multicast, and clients can patch onto any earlier multicast stream.

An underlying requirement for the above schemes is the existence of multicast or broadcast connectivity between the server and the clients. However, IP multicast deployment in the Internet has been slow and even today remains severely limited in scope and reach. Therefore, transmission schemes that can support efficient delivery in such predominantly unicast settings need to be developed. In addition, with the existing schemes, data still has to traverse the entire end-end path from the server to the clients, and network delays can cause substantial playback startup delays at the clients.

An orthogonal technique for reducing server loads, network traffic and access latencies is the use of proxy caches. This technique has proven to be quite effective for delivering Web objects. However, video files can be very large, and traditional techniques for caching entire objects are not appropriate for such media. Caching strategies have been proposed in recent years [6], [7], [8], [9], that cache a portion of a video file at the proxy. In particular, caching an initial prefix of the video [7] has a number of advantages including shielding clients from delays and jitter on the server-proxy path, while reducing traffic along that path. However, existing research has, for the most part, been in the context of unicast delivery of a separate stream to each client. Recent work [10], [11], [12], [13] combines caching with scalable video transmission. However, the focus has mostly been on transmitting a single video or using non-reactive schemes such as periodic broadcast [12], [14] and on networks with end-to-end multicast/broadcast capability. To the best of our knowledge, there has been no systematic evaluation of the resource (proxy cache space and transmis-

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sion bandwidth) issues in techniques that combine proxy prefix caching with reactive transmission for delivering multiple heterogeneous videos accross networks.

In this paper, we explore the combination of proxy prefix caching with proxy-assisted reactive transmission schemes for reducing the transmission cost of multiple heterogeneous videos. Integrating the two techniques has the potential to realize the bandwidth efficiencies of both approaches, while also masking network delays from clients. In patching, for instance, the initial parts of the video are transmitted more frequently than the later parts, suggesting that prefix caching would be particularly effective for bandwidth reduction. Ideally, a proxy-assisted transmission scheme should be incrementally deployable and be able to work with existing unicast-based servers. We address the following questions in this paper:

- *What are suitable proxy-assisted reactive transmission schemes?*
- *For a given transmission scheme, what is the optimal proxy prefix caching scheme that minimizes the transmission cost?*
- *What are the resource (proxy cache space and transmission bandwidth) tradeoffs for the different transmission schemes?*

A. Contributions

The following are the main contributions of this work:

- We develop a generalized allocation technique for analytically determining the solution to the second question posed above. It is general in that it applies to any reactive transmission scheme. It is transmission-scheme aware in that the allocation is based on the transmission cost of a given scheme.
- Starting from traditional reactive transmission schemes, we develop corresponding schemes that use proxy prefix caching as an integral part for bandwidth-efficient delivery in Internet-like environments, where the end-end network connections provide unicast-only service, or at best offers multicast capability only on the last mile proxy-client path.
- We use the optimal cache allocation technique in conjunction with the developed transmission schemes to quantitatively explore the impact of the choice of transmission scheme, cache allocation policy, proxy cache size, and availability of unicast versus multicast capability, on the resultant transmission cost. We develop guidelines for aggregate proxy cache sizing, and identify the combination of transmission and caching schemes that provides the best performance under different scenarios.

The remainder of the paper is organized as follows. Section II presents the problem setting, and introduces key concepts and terminology used in the remainder of the paper. Section III presents our optimal proxy prefix caching technique. Section IV presents a set of proxy-assisted reactive transmission schemes. Our evaluations are presented in Section V. Finally, Section VI concludes the paper and describes ongoing work.

II. Problem Setting and Model

Consider a group of clients receiving videos streamed across the Internet from a server via a single proxy (Fig. 1). We assume

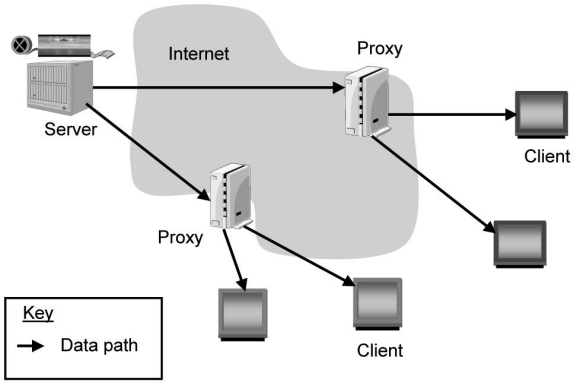


Fig. 1. **Streaming video in the Internet:** The video stream originates from a remote server and travels through the network to the end client. The proxies performing prefix caching are located close to the clients, e.g., at the head-end of the local access network.

that clients always request playback from the beginning of a video. The proxy intercepts the client request and, if a prefix of the video is present locally, streams the prefix directly to the client. If the video is not stored in its entirety at the proxy, the latter contacts the server for the suffix of the stream, and relays the incoming data to the client.

In today's Internet, the network route from the server to the client often traverses multiple ISP domains, and predominantly uses unicast delivery, since IP Multicast is not widely deployed. We note that while many-to-many inter-domain multicast has been slow to be deployed, one-to-many intra-domain multicast (as would be used in an enterprise or cable/DSL-based last-hop network environment) is much simpler to deploy and manage [15]. We therefore assume that the server-proxy network path is unicast-enabled, while the network paths from the proxy to the clients are either unicast or multicast/broadcast enabled. Since the proxy is located close to the clients, we assume the bandwidth required to send one bit from the proxy to multiple clients using multicast/broadcast is still one bit. Finally, for simplicity of exposition, we focus on a single server and a single proxy. The multiple-proxy case is discussed in Section VI.

A. Model

We next provide a formal model of the system, and introduce notation and key concepts that will be used in the rest of the paper. Table I presents the key parameters in the model.

We consider a server with a repository of N Constant-Bit-Rate (CBR) videos. We assume the access probabilities of all the videos and the aggregate access rate to the video repository are known *a priori*. In a real system, these parameters can be obtained by monitoring the system. Without loss of generality, we number the videos in non-increasing order of their access probabilities. Let f_i be the access probability of video i, $\sum_{i=1}^{N} f_i = 1$. f_i measures the relative popularity of a video: every access to the video repository has a probability f_i of requesting video i. Let λ_i be the access rate of video i and λ be the aggregate access rate to the video repository. Then $\lambda_i = \lambda f_i, 1 \leq i \leq N$.

We introduce a *caching grain* of size u to be the smallest unit of cache allocation and all allocations are in multiples of

this unit. It can be one bit or 1 minute's worth of data, etc. We express the size of video i and the proxy cache size as a multiple of a caching grain. Video i has playback bandwidth b_i bps, length L_i seconds, and size n_i units, $n_i u = b_i L_i$. We assume that the proxy can store S units and $S \leq \sum_{i=1}^{N} n_i$. The *storage vector* $v = (v_1, v_2, \cdots, v_N)$ specifies that a prefix of length v_i seconds for each video i is cached at the proxy, $i = 1, 2, \cdots, N$. Note that the videos cached at the proxy cannot exceed the storage constraint of the proxy, that is, $\sum_{i=1}^{N} b_i v_i \leq uS$. Let c_s and c_p respectively represent the costs associated with transmitting one bit of video data on the server-proxy path and on the proxy-client path. Our goal is to develop appropriate transmission and caching schemes that minimize the mean transmission cost per unit time aggregated over all the videos in the repository, i.e., $\sum_{i=1}^{N} C_i(v_i)$, where $C_i(v_i)$ is the transmission cost per unit time for video i when a prefix of length v_i of the video is cached at the proxy. In the rest of the paper, unless otherwise stated, we shall use the term *transmission cost* to refer to this metric.

For simplicity of exposition, we ignore network propagation latency. All the results can be extended in a straightforward manner when network propagation latency is considered [16]. On receiving a client request for a video, the proxy calculates a *transmission schedule* based on the predetermined transmission scheme. This transmission schedule specifies, for each frame in the video, when and on what *transmission channel* (unicast or multicast connection) it will be transmitted by the proxy. The proxy also determines and requests the suffix from the server. A *reception schedule* is transmitted from the proxy to the client. It specifies, for each frame in the video, when and from which transmission channel the client should receive that frame. Note that a client may need to receive data from multiple transmission channels simultaneously. Frames received ahead of their playback times are stored in a client-side workahead buffer. For simplicity, we shall assume the client has sufficient buffer space to accommodate an entire video clip. Finally note that, in our approach, the server only needs to transmit via unicast a suffix of the video requested by the proxy. Our delivery techniques are therefore incrementally deployable as these can work with existing predominantly unicast-based media servers, in the context of existing streaming protocols such as RTSP [17], and require no additional server-side functionality.

Para.	Definition
N	Number of videos
L_i	Length of video i (sec.)
b_i	Mean bandwidth of video i (bits per sec.)
u	Caching grain
n_i	Size of video i (units)
f_i	Access probability of video i
λ_i	Request rate for video i
λ	Aggregate request arrival rate
S	Proxy cache size (units)
v_i	Length (sec) of cached prefix for video i
v	Storage vector, $v = (v_1, v_2, \cdots, v_N)$
c_s	Transmission cost on server-proxy path (per bit)
c_p	Transmission cost on proxy-client path (per bit)
$C_i(v_i)$	Transmission cost per unit time for video i when a prefix of length v_i for video i is cached

TABLE I
PARAMETERS IN THE MODEL.

III. Optimal Proxy Cache Allocation

We next propose a general technique to determine the optimal proxy prefix cache allocation for any given proxy-assisted transmission scheme. For a given transmission scheme, the average transmission cost per unit of time for video i, $C_i(v_i)$, is a function of the prefix v_i cached at the proxy, $0 \leq v_i \leq L_i$. We make no assumption regarding $C_i(v_i)$; it may not exhibit properties such as monotonicity or convexity. For some transmission schemes, there may not even exist a closed-form expression for $C_i(v_i)$. In this case we assume that this value can be obtained by monitoring a running system.

Recall that we use a caching grain u as the smallest unit of cache allocation (see Section II). The size of video i is n_i units and the size of the proxy is S units. Let $A_i = \{m_i \mid 0 \leq m_i \leq n_i\}$ denote the set of possible prefixes for video i, where m_i units is the size and $m_i u / b_i$ seconds is the length of a possible prefix of video i. Let $saving(m_i)$ denote the saving in transmission cost when caching an m_i-unit prefix of video i over caching no prefix of the video at the proxy, i.e., $saving(m_i) = C_i(0) - C_i(m_i u / b_i)$. Our goal is to maximize the aggregate savings and, hence, minimize the aggregate transmission cost over all the videos. The optimization problem can therefore be formulated as :

$$\text{maximize: } \sum_{i=1}^{N} saving(m_i)$$

$$\text{s.t. } \sum_{i=1}^{N} m_i \leq S, m_i \in A_i$$

Note that this formulation is a variant of the 0-1 knapsack problem, where the items to be placed into the knapsack are partitioned into sets and at most one item from each set can be chosen. We next use the following dynamic programming algorithm to determine the optimal allocation.

Let B be a two-dimensional matrix, where entry $B(i, j)$ represents the maximum saving in the transmission cost when using videos up to video i $(0 \leq i \leq N)$ and j $(0 \leq j \leq S)$ units of the proxy cache.

$$B(i,j) = \begin{cases} 0, & i = 0 \\ \max\{B(i-1,j), B'(i,j)\}, & i > 0 \end{cases}$$

where

$$B'(i,j) = \max_{\forall m_i \in A_i} \{B(i-1, j-m_i) + saving(m_i)\}$$

This matrix is filled in row-order starting from $B(0, j), j = 0, \cdots, S$. The value $B(N, S)$ is the maximum saving in transmission cost when all N videos have been used. The minimum transmission cost is

$$\sum_{i=1}^{N} C_i(0) - B(N, S)$$

since the saving is relative to storing nothing at the proxy. The optimal cache allocation can now be computed as follows. For each entry, we store a pointer to an entry from which this current entry is computed. By tracing back the pointers from the entry $B(N, S)$, the optimal allocation is obtained.

The execution time of the algorithm is $O(NSK)$, where $K = \max_{1 \le i \le N} |A_i|$. If the caching grain is increased by a factor of k, both the number of columns in matrix B and the cardinality of A_i ($1 \le i \le N$) are reduced by a factor of k. Therefore the complexity is reduced by a factor of k^2. In Section V, we shall examine the impact of the choice of caching grain on the resultant transmission cost.

IV. Proxy-assisted Transmission Schemes

In this section, we develop a set of reactive transmission schemes that use proxy prefix caching as an integral part for bandwidth-efficient delivery in Internet-like environments, where the end-end network connections provide unicast-only service, or at best offers multicast capability on the proxy-client path. For each scheme, we develop a closed-form expression for the transmission cost $C_i(v_i)$ associated with video i, $1 \le i \le N$. Detailed derivations are found in [16]. The transmission cost $C_i(v_i)$ is used in Section III to determine the proxy cache allocation for each video that minimizes the aggregate transmission cost. The transmission schemes we propose are completely general and apply to any sequence of client arrivals. However, we shall assume a Poisson arrival process for analyzing the transmission costs. Our ongoing work shows that Poisson arrival is a reasonable and conservative assumption for reactive schemes. A similar conjecture is presented in [18].

A. Unicast suffix batching (SBatch)

SBatch is a simple batching scheme that takes advantage of the video prefix cached at the proxy to provide instantaneous playback to clients. This scheme is designed for environments where the proxy-client path is only unicast-capable.

Suppose the first request for video i arrives at time 0. The proxy immediately begins transmitting the video prefix to the client. SBatch schedules the transmission of the suffix from the server to the proxy *as late as possible*, just in time to guarantee discontinuity-free playback at the client. That is, the first frame of the suffix is scheduled to reach the proxy at time v_i, the length of the prefix. For any request arriving in time $(0, v_i]$, the proxy just forwards the single incoming suffix (of length $L_i - v_i$) to the new client, and no new suffix transmission is needed from the server. In effect, multiple demands for the suffix of the video are batched together. Note that in contrast to traditional batching, SBatch does not incur any playback startup delay. Assuming a Poisson arrival process, the average number of requests in time $[0, v_i]$ is $1 + v_i\lambda_i$. The average transmission cost for delivering video i is

$$C_i(v_i) = (c_s \frac{L_i - v_i}{1 + v_i\lambda_i} + c_p L_i)\lambda_i b_i$$

where the first and the second term in the sum corresponds to the server-proxy and proxy-client transmission cost respectively.

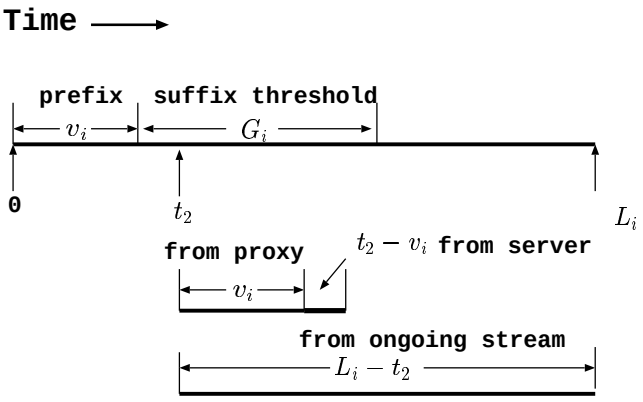


Fig. 2. Unicast patching with prefix caching (UPatch).

When $v_i = 0$ ($v_i = L_i$), video i is transmitted from the server (proxy) using unicast, since it is impossible to batch multiple requests.

B. Unicast patching with prefix caching (UPatch)

SBatch can be further improved by using patching for the suffix. Note that here we use patching in the context of unicast. This is possible because the proxy can forward one copy of the data from the server to multiple clients.

Suppose that the first request for video i arrives at time 0 and the suffix reaches the proxy from the server at time v_i, as shown in Fig. 2. Suppose another client's request for video i comes at time $t_2, v_i < t_2 < L_i$. The proxy can schedule a transmission of the complete suffix at time $t_2 + v_i$ from the server. Another option is to schedule a patch of $[v_i, t_2)$ of the suffix from the server since segment $[t_2, L_i]$ has already been scheduled to be transmitted. Note that this patch can be scheduled at time $t_2 + v_i$ so that the client is still required to receive from at most two channels at the same time. The decision to transmit a complete suffix or a patch depends on a *suffix threshold* G_i, measured from the beginning of the suffix. If one request arrives within G_i units from when the nearest complete transmission of the suffix was started, the proxy schedules a patch from the server for it. Otherwise, it starts a new complete transmission of the suffix. Assuming a Poisson arrival process, between the initiations of two consecutive transmissions of the suffix, the average number of requests is $1 + \lambda_i(v_i + G_i)$. The average transmission cost for video i is

$$C_i(v_i) = c_s\lambda_i b_i \frac{\lambda_i G_i^2/2 + L_i - v_i}{1 + \lambda_i(v_i + G_i)} + c_p\lambda_i b_i L_i$$

where the first and the second term corresponds to the server-proxy and the proxy-client transmission cost respectively.

The suffix threshold G_i is chosen to minimize the transmission cost for video i for a given prefix v_i. Finally, when $v_i = L_i$, video i is transmitted from the proxy to clients using unicast.

C. Multicast patching with prefix caching (MPatch)

If the proxy-client path is multicast capable, the proxy can use a multicast transmission scheme. We describe MPatch, a patching scheme that exploits prefix caching at the proxy.

Suppose the first request for video i arrives at time 0 (Fig. 3). Then the proxy starts to transmit the prefix of the video via multicast at time 0. The server starts to transmit the suffix of the video to the proxy at time v_i and the proxy transmits the received data via multicast to the clients. Later requests can start a new complete multicast stream or join the ongoing multicast of the stream and use a separate unicast channels to obtain the missing data. Let T_i be a threshold to regulate the frequency at which the complete stream is transmitted. Suppose a request arrives at t_2 ($0 < t_2 \leq T_i$) units after the beginning of the nearest ongoing complete stream. Video delivery for this client can be classified into the following two cases depending on the relationship of v_i and T_i.

- Case 1: $T_i \leq v_i \leq L_i$. This is shown in Fig. 3 (a). The client receives segment $[0, t_2]$ from a separate channel via unicast from the proxy and segment $(t_2, L_i]$ via the ongoing multicast stream. Assuming a Poisson arrival, the transmission cost function in this case $g_1(v_i, T_i)$ is

$$g_1(v_i, T_i) = \frac{\lambda_i b_i}{1+\lambda_i T_i}[(L_i - v_i)c_s + L_i c_p + \frac{\lambda_i {T_i}^2}{2} c_p]$$

  This is computed by modelling the patching system as a renewal process, since requests arriving more than T_i units after the previous complete stream initiates a new complete stream. The above computation is carried out over the interval between the initiation of two complete streams. In this interval, the average total length of patches is $\frac{\lambda_i {T_i}^2}{2}$ [4].
- Case 2: $0 \leq v_i < T_i$. This is shown in Fig. 3 (b). If $0 < t_2 \leq v_i$, then the transmission mechanism is the same as in Case 1. If $v_i < t_2 \leq T_i$, the client receives segment $[0, v_i]$ from a separate channel via unicast from the proxy and receives segment $(t_2, L_i]$ via the ongoing multicast stream. Segment $(v_i, t_2]$ is transmitted from the server to the client via the proxy using unicast. Assuming a Poisson arrival, the transmission cost function in this case $g_2(v_i, T_i)$ is

$$g_2(v_i, T_i) = \frac{\lambda_i b_i}{1+\lambda_i T_i}[(L_i - v_i)c_s + L_i c_p + \frac{\lambda_i {v_i}^2}{2} c_p + \frac{\lambda_i (T_i - v_i)^2}{2}(c_s + c_p)]$$

  Similar to Case 1, this computation is also carried out over the interval between the initiation of two complete streams. In this interval, the average total length of patches from the proxy is $\frac{\lambda_i {T_i}^2}{2}$. The average total length of patches from the server is $\frac{\lambda_i (T_i - v_i)^2}{2}$. This is because the average number of arrivals in this time interval is $\lambda_i(T_i - v_i)$ with average length of patch of $(T_i - v_i)/2$.

Let $h_k(v_i)$ be the minimum transmission cost in Case k, $k = 1, 2$. That is,

$$h_k(v_i) = \min_{T_i}\{g_k(v_i, T_i), 0 \leq T_i \leq L_i\}, k = 1, 2$$

For a given prefix v_i, the average transmission cost is

$$C_i(v_i) = \min\{h_1(v_i), h_2(v_i)\}$$

Finally, note that if video i is streamed entirely from a single location (either the server or the proxy), the MPatch transmission scheme reduces to Controlled Multicast (CM) patching [4].

D. Multicast merging with prefix caching (MMerge)

The key issue in stream merging is deciding how to merge a later stream into an earlier stream. Closest Target [5] is one online heuristic merging policy whose performance is close to optimal offline stream merging. This policy chooses the closest earlier stream still in the system as the next merge target.

Our MMerge scheme integrates proxy caching and stream merging. It uses the Closest Target policy to decide how to merge a later stream into an earlier stream. For a video segment required by the client, if a prefix of the segment is at the proxy, it is transmitted directly from the proxy to the client; the suffix not cached at the proxy is transmitted from the server *as late as possible* while still ensuring continuous playback at the client. Let p_j be the probability of requiring a j-second prefix per unit of time for video i, $0 \leq j \leq L_i$. Then the average transmission cost for video i is

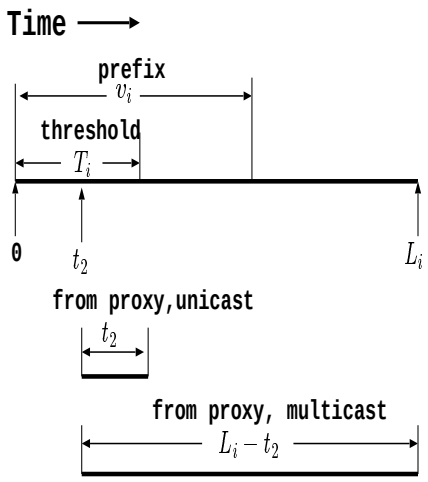
$$C_i(v_i) = \sum_{j=1}^{v_i} j p_j b_i c_p + \sum_{j=v_i+1}^{L_i} (j(c_p + c_s) - v_i c_s) p_j b_i$$

where the first summation in the sum corresponds to the case where the required prefix streams are no longer than the prefix cached at the proxy, while the second summation corresponds to the case where the required prefix streams are longer than the prefix at the proxy. Finally, note that if video i is streamed entirely from a single location (either the server or the proxy), MMerge reduces to Closest Target stream merging.

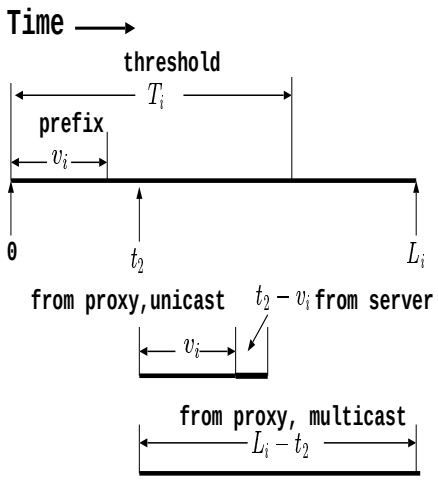
V. Performance Evaluation

In this section, we examine the resource tradeoffs under the previously described caching and transmission schemes. We consider a repository of 100 CBR video clips with access probabilities drawn from a Zipf distribution with parameter $\theta = 0.271$ [1]. For simplicity, we assume all the videos are two hours long, and have the same bandwidth. We normalize the transmission cost by both the video bandwidth and the value of c_s. That is, the normalized transmission cost is $\sum_{i=1}^{N} C_i(v_i)/(c_s b_i)$. Let $\hat{c_p} = c_p/c_s$. In this section, we assume $\hat{c_p} \in [0, 1]$. Observe that $\hat{c_p} = 0$ corresponds to $c_p = 0$ and $\hat{c_p} = 1$ corresponds $c_p = c_s$. We represent the proxy cache size as a percentage, r, of the size of the video repository. We consider 10 seconds and 1 minute's worth of data as the caching grain for the optimal prefix caching. Our evaluation shows that the transmission costs differ little for these two grains. Therefore, we only provide results using the latter. For MMerge, the probability of requiring a j-second prefix per unit of time for video i is obtained from a 150-hour simulation run.

We first compare the transmission costs using optimal prefix caching and optimal 0-1 caching. Optimal 0-1 caching only allows a video to be cached in its entirety or not at all. We then investigate differences in transmission cost under optimal prefix caching and a heuristic, Proportional Priority (PP) caching. In PP caching, the size of the proxy cache allocated to a video is proportional to the product of the size of the video and its access probability, under the constraint that the allocated space is no larger than the size of the video. PP caching takes account of both the popularity and the size of the video. A similar



(a) Case 1: $T_i \leq v_i \leq L_i$.



(b) Case 2: $0 \leq v_i < T_i$.

Fig. 3. Multicast patching with prefix caching (MPatch).

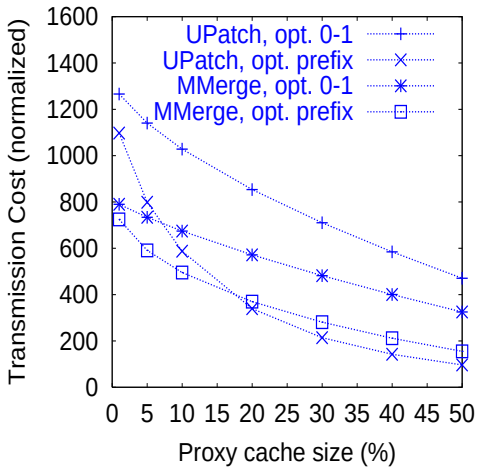


Fig. 4. Normalized transmission cost v.s. proxy cache size, $\lambda = 100$/min, $\hat{c_p} = 0$.

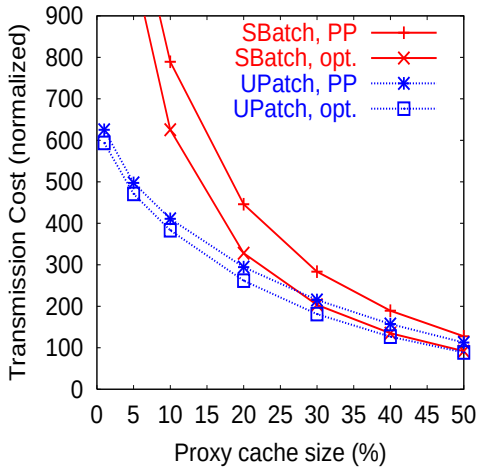


Fig. 5. Normalized transmission cost v.s. proxy cache size, $\lambda = 30$/min, $\hat{c_p} = 0$.

heuristic is suggested in [13]. In our setting, the size of proxy cache allocated to a video is proportional to its popularity under PP caching since all the videos are of the same size. For each scheme, we plot the optimal proxy cache allocation across the videos for small ($r = 1\%$), medium ($r = 10\%$) and large ($r = 50\%$) proxy caches.

A. Optimal prefix caching v.s. optimal 0-1 caching

The allocation under optimal 0-1 caching can be modeled as a 0-1 knapsack problem [16]. When the length and bandwidth of the videos are the same, the optimal 0-1 scheme caches videos in the order of their popularities. We find that optimal prefix caching significantly outperforms optimal 0-1 caching for all the schemes we examine. Fig. 4 plots the transmission costs under the two caching schemes for UPatch and MMerge when $\hat{c_p}$ is 0 and the arrival rate λ is 100 requests per minute. UPatch and MMerge under optimal prefix caching result in substantially lower costs than under optimal 0-1 caching across the range of proxy cache sizes. For instance, when the proxy cache is 20% of the size of the video repository, optimal prefix caching reduces the costs over optimal 0-1 caching by 60% and 35% for UPatch and MMerge respectively. We therefore focus on prefix caching for the rest of the paper.

B. Transmission and caching schemes under unicast

We first investigate the transmission cost when the proxy-client path is only unicast capable. Fig. 5 depicts the transmission cost as a function of r, when $\hat{c_p}$ is 0 and the aggregate arrival rate λ is 30 requests per minute. The performance of SBatch and UPatch under both PP and optimal prefix caching are plotted on the graph. The percentage of reduction by using optimal prefix caching over PP caching increases as the proxy size increases. When $r = 20\%$, the reduction is 26% for SBatch and 11% for UPatch. Our evaluation also shows that the cost reduction using optimal prefix caching over PP caching increases as the aggregate arrival rate increases. The reason will become clear at the end of Section V-B.

We observe from Fig. 5 that a small amount of cache at the proxy results in substantial cost savings for both transmission schemes under optimal prefix caching. For instance, with a

proxy cache that is 10% of the size of the video repository, the transmission costs reduce to 17% and 88% of the corresponding costs without a proxy cache for SBatch and UPatch respectively.

We find that UPatch substantially reduces cost over SBatch under optimal prefix caching, particularly for small and moderate proxy sizes (see Fig. 5). For instance, when $r = 1\%$, the reduction under UPatch over SBatch is 69%. However, this is under the assumption that the optimal threshold for UPatch can be obtained. The choice of the threshold critically impacts the cost savings for UPatch - an arbitrary threshold value can result in performance degradation. Hence for situations where the appropriate threshold cannot be properly determined, SBatch may be preferred. SBatch, being simpler to implement, is also preferred for larger proxy cache sizes, where its performance is very close to that of UPatch.

The above discussion focussed on the case of $\hat{c_p} = 0$. When $\hat{c_p} > 0$, we observe similar performance trends for the different transmission and caching schemes. This is because when the proxy-client path is only unicast-capable, the proxy has to transmit a copy of each data unit separately to each client. Hence, for a fixed $\hat{c_p}$, the transmission costs on the proxy-client path are identical for all transmission (unicast-based) and caching schemes.

Proxy cache allocation across the videos: We next examine the proxy cache allocation for SBatch and UPatch under optimal prefix caching. When the proxy-client path is only unicast-capable, the optimal prefix cache allocation is identical for all values of $\hat{c_p}$ for a given transmission scheme. This is because, as mentioned earlier, the transmission cost on the proxy-client path for a fixed $\hat{c_p}$ does not depend on cache allocation. Therefore allocating the proxy cache to minimize the total transmission cost is the same as that required to minimize the transmission cost on the server-proxy path, which is independent of the value of $\hat{c_p}$. In the following, $\hat{c_p}$ is chosen to be 0.

Fig. 6 depicts the proxy cache allocations under UPatch, for arrival rates of 10 and 100 requests per minute. The proxy cache allocation under SBatch is similar. We see that, when the proxy cache size is small, only the most popular videos are cached. As the the proxy cache size increases, more videos are cached. For low aggregate arrival rates, the size of the proxy storage allocated to a video increases as a function of its access probability. At high arrival rates, the proxy storage tends to be more evenly distributed among all the videos; this differs substantially from the proportional allocation under PP caching and helps to explain the difference in transmission cost under the two caching schemes.

C. Transmission and caching under multicast

We next investigate the transmission cost when the proxy-client path is multicast capable. Fig. 7 shows the normalized transmission cost as a function of r, when $\hat{c_p}$ is 0.5 and the aggregate arrival rate λ is 30 requests per minute. The transmission costs for MPatch and MMerge under optimal prefix caching and PP caching are plotted on the graph. In the case of MPatch, the transmission costs under optimal prefix caching and PP caching are close for very small and large proxy sizes.

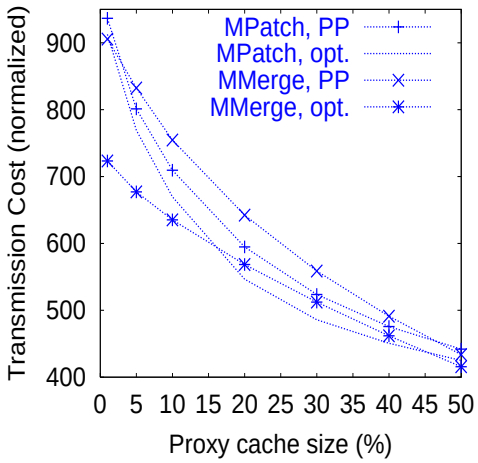


Fig. 7. Normalized transmission cost v.s. proxy cache size when $\lambda = 30$/min and $\hat{c_p} = 0.5$.

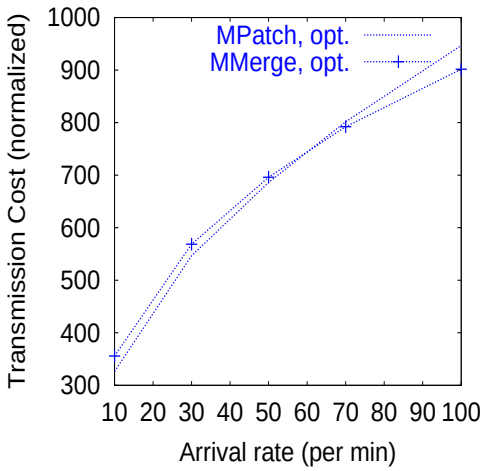


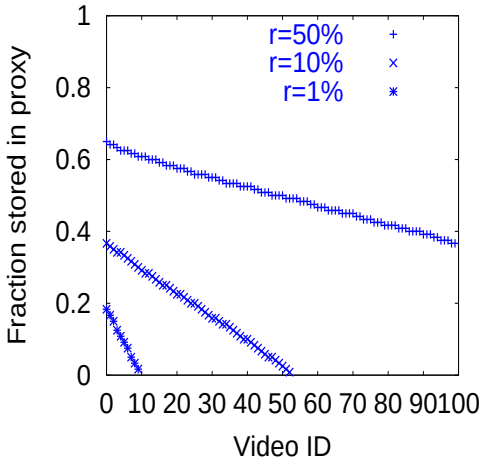
Fig. 8. Normalized transmission cost v.s. arrival rate when $r = 20\%$ and $\hat{c_p} = 0.5$.

In the case of MMerge, the difference in transmission costs under optimal prefix caching and PP caching is large for small proxy cache sizes. For instance, when $r = 1\%$, the transmission cost under optimal prefix caching is 20% lower than that under PP caching.

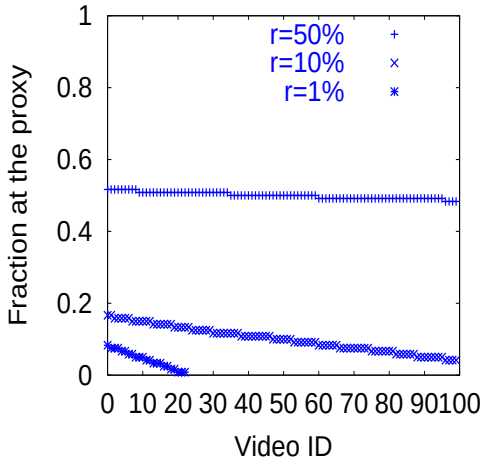
Fig. 7 also demonstrates that a small amount of proxy buffer results in substantial transmission cost savings under optimal prefix caching. With a proxy cache that can hold 10% of the video repository, the transmission costs reduce to 65% and 85% of the corresponding cost without proxy cache for MPatch and MMerge respectively.

It is interesting to notice that proxy-assisted MMerge does not always outperform MPatch. This is different from traditional server-based patching and stream merging, where stream merging always outperforms patching. Fig. 8 depicts the transmission costs for various arrival rates when $r = 20\%$ and $\hat{c_p} = 0.5$. We observe that, MPatch incurs lower transmission cost for low arrival rates and MMerge incurs lower transmission cost for high arrival rates.

Proxy cache allocation across the videos: We next examine the

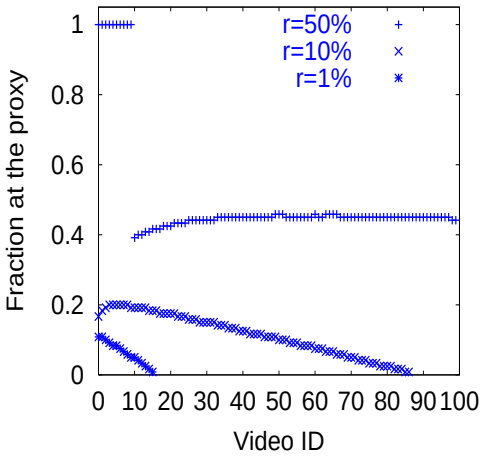


(a) λ=10/min

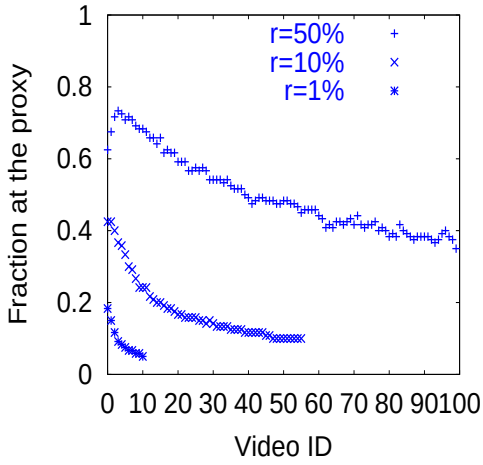


(b) λ=100/min

Fig. 6. Proxy cache allocation for UPatch under optimal prefix caching, $\hat{c_p}$=0.



(a) MPatch.



(b) MMerge.

Fig. 9. Proxy cache allocation for MPatch and MMerge under optimal prefix caching when $\hat{c_p} = 0.1$ and λ=30/min.

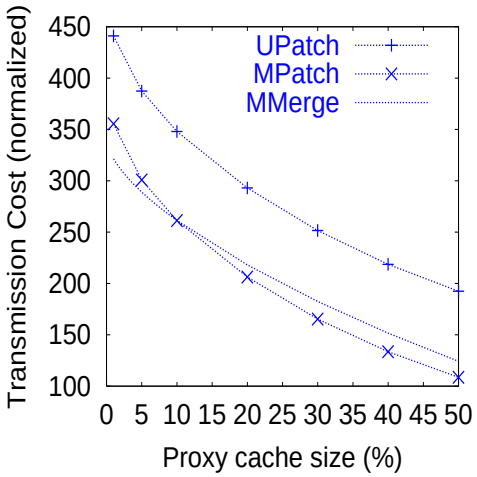
proxy cache allocation for MPatch and MMerge under optimal prefix caching. When $\hat{c_p} = 0$, since the transmission from the proxy to clients does not incur any cost, using multicast or unicast along the proxy-client path does not make any difference to the allocation. Therefore, the allocation for MPatch is identical to UPatch as shown in Fig. 6.

Fig. 9 (a) displays proxy cache allocations for MPatch when $\hat{c_p} = 0.1$ and $\lambda = 30$/min. We find that the size of the proxy cache allocated to a video is not a monotonically increasing function of the access probability. This is because the threshold tends to increase as the access probability decreases. Therefore some less popular videos may require larger prefixes than more popular videos to realize the optimal threshold.

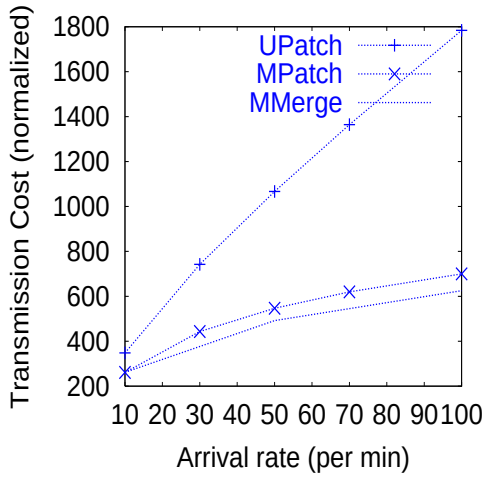
Fig. 9 (b) depicts the proxy cache allocations for MMerge when $\hat{c_p} = 0.1$ and $\lambda = 30$/min. In general, the proxy cache space allocated to a video decreases as its popularity decreases. However, when the proxy caches are large and the arrival rates are high, the size of the proxy cache allocated to a video can increase as the popularity decreases. This is because the average length of prefix streams increases as the popularity (hence the arrival rate) decreases. We also observe that when $\hat{c_p} = 0.1$, only several of the most popular videos are cached for small and moderate proxy caches. When $\hat{c_p} = 0$ (not shown in the figure), proxy cache is more evenly distributed among the videos for small and moderate proxy caches.

D. Comparison between unicast and multicast

When $\hat{c_p} > 0$, using multicast instead of unicast along the proxy-client path results in substantial savings. We set $\hat{c_p}$ to 0.1 in the following. Fig. 10 (a) depicts the normalized transmission costs of UPatch, MPatch and MMerge under optimal prefix caching when $\lambda = 10$/min. We observe, in this case, that the transmission costs of MPatch and MMerge are significantly lower than those of UPatch across the range of proxy cache sizes. Fig. 10 (b) shows the transmission costs as the arrival rate increases from 10 to 100 requests per minute when $r = 10\%$. The savings under MPatch and MMerge over UPatch increase as the arrival rate increases. When the arrival rate is 10 requests per minute, transmission costs under MPatch is 25% lower than under UPatch. When the arrival rate is 100 requests per minute,



(a) $\lambda = 10$/min.



(b) $r = 10\%$.

Fig. 10. Comparison between unicast and multicast schemes when $\hat{c_p} = 0.1$. (a) Normalized transmission cost v.s. proxy cache size. (b) Normalized transmission cost v.s. arrival rate.

the reduction becomes 61%. This clearly illustrates the benefits of using multicast locally, over the proxy-client path.

E. Summary of Results

We summarize the key inferences from our evaluation.

- For the same proxy size, using prefix caching for a set of videos results in significantly lower transmission costs compared to entire-object caching policies. Under optimal prefix caching, even a relatively small proxy cache (10%-20% of the video repository) is sufficient to realize substantial savings in transmission cost.
- The allocation under optimal prefix caching is sensitive to the transmission scheme, the aggregate arrival rate and the value of $\hat{c_p}$. Optimal prefix caching can substantially outperform transmission cost agnostic PP caching, particularly for high arrival rates. However, in some cases, such as when the arrival rates are low, the simpler PP caching performs reasonably well.
- Carefully designed reactive transmission schemes coupled with optimal proxy prefix caching can produce significant cost savings over using unicast delivery, even when the underlying network offers only unicast service. Our results also suggest that, unlike the case of server-client transmission over a multicast-capable network, stream merging does not always outperform patching in the presence of proxy prefix caching.
- The optimal cache allocation can realize most of the cost savings even with a relatively coarse (few minutes of data) cache allocation grain. The computation overhead of the scheme is well within the capabilities of todays desktop PCs, suggesting that the cache allocation scheme can be deployed in practice.

VI. Conclusions and Ongoing work

In this paper, we presented a technique to determine, for a given proxy-assisted transmission scheme, the *optimal* proxy prefix caching for a set of videos that minimizes the aggregate transmission cost. We presented and explored a set of proxy-assisted reactive transmission schemes that exploit proxy prefix caching to provide bandwidth efficient delivery. Our evaluations demonstrate that, even with a relatively small proxy cache, carefully designed transmission schemes under optimal prefix caching can lead to significant cost reductions.

As ongoing work, we are pursuing the following directions. (i) We are evaluating the performance of optimal prefix caching and PP caching under realistic network settings. (ii) Our results apply directly to multiple-proxy Content Distribution Networks where the server has unicast connections to the proxies, each proxy serves a different set of clients (no overlapping), and the proxies do not interact. We are currently exploring scenarios where the connections between the server and the proxies are multicast-capable, and proxies can interact. (iii) Our schemes apply equally to Variable-Bit-Rate (VBR) video transmission, and the analysis presented here can be extended in a straightforward manner to the VBR case. Quantitative evaluation of the different schemes for VBR video distribution is part of ongoing work.

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